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AN EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF STIRLING SPACE POWER CONVERTER HEATER HEAD

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SUMMARY

NASA has identified the Stirling power converter as a prime candidate for the next generation power system for space applications requiring 60 000 hr of operation. To meet this long-term goal, several critical components of the power converter have been analyzed using advanced structural assessment methods. Perhaps the most critical component, because of its geometric complexity and operating environment, is the power converter's heater head. This report describes the life assessment of the heater head which includes the characterization of a viscoplastic material model, the thermal and structural analyses of the heater head, and the interpolation of fatigue and creep test results of a nickel-base superalloy, Udimet 720 LI (Low Inclusions), at several elevated temperatures for life prediction purposes.

INTRODUCTION

Today's spacecraft consume relatively low power levels, supplied by the state-of-the-art solar arrays and storage batteries. Tomorrow's power needs will increase significantly as space-based missions evolve. Dynamic nuclear power systems utilizing the Stirling cycle show promise in meeting these needs.

Space power generating systems have stringent design requirements. They must be safe to launch and deploy, be reliable when called upon, exhibit a high efficiency-to-mass ratio, be economically feasible, and have long-time structural durability. Obvious trade-offs must be addressed among these requirements. In particular, low mass versus high durability trade-offs are of paramount concern for high-temperature, life-limiting components such as the heater head of a Stirling engine. The NASA Lewis Stirling Space Power Converter (SSPC) Project is using a geometrically complex heater head referred to as the "starfish" heater head (fig. 1).

The SSPC project and the starfish heater head are discussed in references 1 to 3. A cross section of the Stirling Power Converter is shown in figure 2. The Stirling Space Power Project was performed as a part of the High Capacity Power element of the NASA Civil Space Technology Initiative (CSTI). The work was primarily done by Mechanical Technology, Inc., Latham, New York under contract to NASA Lewis Research Center.

The heater head is a structural component which transfers heat from the sodium in the heat pipe to the working fluid (helium) of the power converter; it also includes the outer housing for the regenerator and cooler sections of the engine. The starfish heater is comprised of 50 fins, each containing 28 thin-walled gas passages. The fins are exposed to liquid sodium at 775 °C which can attack the base metal of the starfish and degrade its durability. Further, the thin gas passage walls are under a biaxial stress state resulting from the high operating pressures of the converter (15 ± 1.8 MPa) (ref. 2). Optimizing for operating performance by decreasing the thickness of the finned walls will result in higher thermal efficiency and lower mass, but durability will be compromised as primary stresses within the wall increase. Conversely, increasing the wall thickness will provide greater durability with a decrease in efficiency and increase in mass. An optimal thickness can be arrived at only if the long-life durability relations are known with sufficient accuracy. The established lifetime must, of course, be sufficiently long to warrant investment of funds for design, construction, and deployment.

The minimum life requirement for space Stirling power systems is 60 000 hr, with maximum operating temperatures in the range of 700 to 775 °C (ref. 4). At high operating temperature for extended periods of time, material response will invariably deviate from linear elastic behavior. Hot-section components of Stirling engines are subject to severe thermal gradients and high mechanical loads. Inelastic deformation will likely be induced in localized regions leading to eventual creep cracking and fatigue crack propagation. Udimet 720 LI (Low Inclusions), a cast-wrought nickel-base superalloy, is being considered for the starfish heater head material because of its long-term microstructural stability. It is a unique, nickel-base gamma prime strengthened superalloy which is used in elevated temperature applications requiring either high tensile strength with a fine-grain structure or high creep resistance with coarse-grain structure. In addition to its excellent strength, it has superior hot-corrosion resistance when compared to other wrought superalloys (Internal report from Sczerzenie, et al.: Udimet 720 Alloy. Special Metal Corp. Report TR–8–002, May 1978).

This report presents a final summary of a heater head life assessment conducted for the Stirling Space Power Converter Project at NASA Lewis. Included in this summary are Udimet 720 LI test data used for characterization of a viscoplastic constitutive model, results for viscoplastic and elastoplastic finite element analyses of the starfish heater head, and a life assessment based on the previous information.

It should be noted, that due to the lack of reliable stress-corrosion test data for Udimet 720 LI, this life assessment of the starfish heater head does not account for damage to the Udimet 720 LI resulting from direct contact with the liquid sodium. Thus, this life assessment represents the best case scenario, and the appropriate precautions should be placed on these results.

This report presents a summary of the stress-strain data collected through a series of fatigue and creep tests performed on Udimet 720 LI, describes the applicability of the material viscoplastic constitutive model developed by Freed (ref. 5), and includes a set of viscoplastic and elastoplastic finite element analyses of the starfish head under thermo-mechanical loading conditions using the MARC finite element code (ref. 6).

EXPERIMENTAL PROCEDURE

Material and Specimens

Udimet 720 LI, 0.31 mm diameter, solid round specimens were machined from a single heat of commercial grade Udimet 720 bar stock. The chemical composition of the alloy in weight percent is shown in table I (Internal report from Sczerzenie, et al.: Udimet 720 Alloy. Special Metal Corp. Report TR-8-002, May 1978).

Test Apparatus and Procedures

All the tests were performed on a 100-kN servohydraulic axial test system. A personal computer was used for test control and data acquisition. Strains were measured using a commercially available axial extensometer. Two indentations were pressed into the outer surface of the specimen with a precision fixture so that the conical tips of the extensometer probes could be mounted. Specimen heating was accomplished using a 5-kW induction heating system coupled to a movable three-coil heating fixture (ref. 7). This arrangement permitted the adjustment of the heat input distribution, and thus allowed the thermal gradient within the gage section of each specimen to be kept to a minimum at any test temperature. Chromel-Alumel thermocouples, spot-welded just outside the gage section, were used to monitor and control the specimen temperature. Variation of the temperature along the uniform section of the specimen was within 1 percent of the nominal temperature. In each test, cyclic stress-strain data were acquired until failure of the specimen.

ANALYTICAL PROCEDURE

Freed's Viscoplastic Model

Analytical studies of engine hot section components such as turbine blades (ref. 8) and combustor liners (ref. 9) have demonstrated that classical methods do not always accurately predict the cyclic response of a structure, simply because of the lack of interaction between the plasticity and creep. In addition to the inability to model the interaction between creep and plasticity, most of the classical plasticity theories suffer from an inability to model material behavior under cyclic loading conditions. Under such loading conditions, the classical theories are unable to predict the strain hardening/softening characteristics of the material. These limitations in constitutive modeling behavior had been discussed in some depth by Krempl (ref. 10).

In light of the above information, it is apparent that the best approach to improve the prediction of inelastic behavior of metals at high temperatures is the development of unified viscoplastic theories. This not only satisfies the experimental observation of the inseparability of creep and plastic strains but also handles interaction and various deformation phenomena in a more natural manner. The mathematical structure of the viscoplastic constitutive material model being used here for the Stirling engine hot-section component structural assessment incorporates two state variables. They are (1) the yield function and (2) the back stress. The yield strength accounts for isotropic hardening effects, while the back stress accounts for kinematic hardening effects. These state variables are considered to evolve phenomenologically through competitive processes associated with strain hardening, strain-induced dynamic recovery, and time-induced thermal recovery. The model in its general form is written as follows (ref. 5):

$$\dot{\sigma} = E\left(\dot{\varepsilon} - \dot{\varepsilon}_1 - \dot{\varepsilon}_T\right) \tag{1}$$

$$\dot{\varepsilon}_1 = \theta(T) f\left(\langle \|LS - B\| - Y \rangle\right) \tag{2}$$

$$\dot{B} = h_1 \dot{\varepsilon}_1 - r_1 B \|\dot{\varepsilon}_1\| \tag{3}$$

$$\dot{Y} = h_2 \|\dot{\varepsilon}_1\| - r_2 \theta(T) \tag{4}$$

where

$\dot{\sigma}$	stress rate
E	modulus of elasticity
$\dot{\varepsilon}$	total strain rate
$\dot{\varepsilon}_I$	inelastic strain rate
$\dot{\varepsilon}_T$	thermal strain rate
$\theta(T)$	function of temperature

f(X) function of X

$\|X\|$ $\sqrt{(2/3)X_{ij}X_{ij}}$

L limiting state function

S deviation stress tensor

B back stress tensor

Y yield function

h_1,h_2 strain hardening functions

r_1,r_2 recovery functions

Equation (1) assumes that the stress rate is proportional to the elastic strain rate. Equation (2) is the flow equation which defines the inelastic rate as a function of applied stress, internal state variables, and temperature, while equations (3) and (4) specify how the internal state variables evolve during deformation processes. The Macauley bracket operator $\langle \|S - B\| - Y \rangle$ has a value of 0 whenever $\|S - B\| < Y$ (defining the elastic domain), or a value of $\|S - B\| - Y$ whenever $\|S - B\| > Y$ (defining the viscoplastic domain), with $\|S - B\| = Y$ establishing the yield surface.

The equations are chosen to reflect a particular metallurgical mechanism or phenomenological behavior. More information about the model is available in reference 5.

To establish the temperature dependence of the viscoplastic model, the material constants required were determined using the creep test data obtained. The first step was the calculation of the steady-state **Zener parameter** (ref. 11), a temperature normalized measure of the inelastic strain rate, utilizing the test data. The parameter was then plotted against its associated flow stress to obtain the curve which characterizes the steady-state creep behavior of the alloy (fig. 3). In the second step of the characterization process, the maximum values that can be attained by the stress and the internal variables were established via an estimation of the maximum Zener parameter. The final step included the partitioning of the internal stress between isotropic and kinematic contributions through the material constant f, and the quantification of the monotonic/cyclic interaction effects. Saturated, stress-strain hysteresis loops of the Udimet 720 were used during this process. The Levenberg-Marquardt minimization method was utilized to determine an optimal value for the material constant f (along with D). Details of the characterization process of Freed's viscoplastic model were reported in reference 12.

Other key requirements for the viscoplastic model are the material constants. These constants are determined through laboratory testing by performing tensile, fatigue, and creep tests. The tests are conducted on smooth, uniaxial bar specimens fabricated from the same material and with the same heat treatment and composition specified for the component.

Finite Element Analysis

A three-dimensional finite element model consisting of 5775 eight-node isoparametric brick elements and 8025 nodes was constructed using PATRAN Graphics (ref. 13) (fig. 4). Boundary conditions were applied to constrain all the nodes on the base to lie on a disk plane. Additional boundary conditions were imposed to prevent rigid body motion. Prior to conducting the analysis, a heat transfer analysis was performed to establish heater head temperature profiles. The thermal boundary conditions covered both convection and conduction phenomena experienced by the heater head. Figure 5 shows the temperature distribution obtained for the heat transfer analysis. Note the large temperature gradient in the regenerator outer wall. In addition to the thermal load, a mechanical load based on gas pressure was included and its severity is illustrated in figure 6 in terms of load versus time. Due to the high computational COST, a 10 000 hr loading cycle was considered for the analysis.

Viscoplastic Analysis

The viscoplastic model, developed by Freed (ref. 5), and characterized for Udimet 720 LI, was employed to describe the time-dependent inelastic behavior of the material. This viscoplastic model, in its general multiaxial form, was implemented in the finite element program MARC by Arya (ref. 14). This was done through the MARC user subroutine HYPELA employing a self-adaptive time integration strategy (ref. 15) and based on the explicit Forward Euler method. It provided accurate and efficient integration of the constitutive equations. The implementation was first exercised on several uniaxial problems involving isothermal and nonisothermal loadings. The results obtained from the tests were compared with experimental data to validate the finite element implementation. Figure 7 represents a comparison of stress versus strain data for Udimet 720 at 675 °C between the viscoplastic model and the experiment for a uniaxial case. Good agreement was achieved which indicates a successful implementation of the model. Later the applicability of the model was tested via a stress analysis of the Stirling engine heater head.

Stress Analysis

An elastoplastic analysis was conducted under creep conditions using the classical plasticity theory to evaluate the stress-strain relationship and compare it with the viscoplastic calculations. The calculations were conducted by dividing the load history into a series of incremental load steps which are sequentially analyzed. Consequently, these incremental loads are modified by residual load correction vectors to-ensure that the solution does not drift from a state of equilibrium. This option is invoked by computing the difference between the external and internal forces summed over all the elements at the end of the previous increment. The convergence for the iterative plasticity analysis is indicated when the strain energy used in assembling the stiffness matrix approximately equals the energy change resulting from the incremental solution. The plasticity algorithm in the MARC code is based on a tangent stiffness approach which means that the stiffness matrix is reformulated and reassembled for every plastic load increment.

The automatic time incrementation has also been incorporated in the incrementation procedures to allow for time step control under large cyclic stress and inelastic strain excursions. The control is achieved by limiting the maximum stress and inelastic strain change permitted at any time increment. All the calculations were based on incremental plasticity theory using Von Mises yield criterion, the normality flow rule, and a kinematic hardening model. The material elasto-plastic behavior was specified by the yield strengths and work hardening properties in the transverse and longitudinal directions. Data for Udimet 710 in combination with the experimental data on Udimet 720 LI were utilized to generate the work hardening information for the analyses (ref. 16).

RESULTS AND DISCUSSION

Experimental results for the Udimet 720 LI and an estimation of design life for the starfish heater head will be presented in this section. Also a discussion of the Finite Element Analysis (FEA) used to confirm the prime contractor's analysis and estimate stress redistributions caused by Visco-elastoplastic material behavior is included. It should be noted that the primary purpose of the data base generated for this study was to characterize the constitutive model used for this FEA. Thus, test conditions and test termination points were chosen for this purpose and not to generate tensile, creep rupture, or fatigue data. Likewise, the life assessment was based on this data due to the limited existing Udimet 720 LI data for the design conditions.

Test Results

Tables II to IV present tensile, creep, and fatigue data acquired from experiments conducted on Udimet 720 LI at various test conditions. These tables (II and III) contain the tensile and creep results that were used in the model characterization and subsequent life assessment. The deformation response of Udimet 720 LI is presented in figure 8. Note that test temperatures ranged from 625 to 820 °C for all test types. These temperatures were chosen to create an envelope of material response around the proposed operating temperature (775 °C) of the starfish heater head. Likewise, for material model characterization purposes, creep stresses ranged between 165 and 827 MPa to encompass over 12 different stress-temperature combinations.

Tensile tests.—As can be seen in figure 8 and due to instrumentation limitations, tensile tests were stopped at 5 percent strain and were not taken to specimen fracture. Four of the tensile tests were used to investigate the strain rate sensitivity of Udimet 720 LI. Tests were conducted at 775 °C with strain rates ranging from 10^{-4} to 10^{-3}/sec. Tensile results (table II) indicate that the Udimet 720 LI tensile properties were not significantly influenced by strain rate. Therefore, a strain loading rate of (10^{-3}/sec) was used for subsequent tensile, creep , and deformation tests. Figure 8 shows the tensile data at a strain rate of 0.001 sec^{-1} for five temperatures and moduli; it clearly indicates the combined effects of the latter two factors.

Creep tests.—Creep tests were conducted at 14 different stress-temperature conditions to characterize the Zener parameter for the viscoplastic analysis and provide data for subsequent heater head life approximation. Tests were terminated after steady-state creep was achieved. Table III shows steady-state creep rates for all the tests at different temperatures and stress conditions. The temperature ranged from 625 to 820 °C. The stress level was varied from 165 to 827 MPa as the steady-state creep rate changed from a minimum of 1.94×10^{-5} to a maximum of 4.22×10^{-3}/hr. One of the specimens tested was ruptured. It was the one tested at 662 MPa and 775 °C. It took 4 hr to rupture.

Trends in steady-state creep rates with respect to stress and temperature are shown in figure 9. The 675 °C data has some scatter in creep rates which is typical for creep data. It is noted that the creep rates with respect to stress were similar for 625, 675, and 820 °C. The only exception was the 820 °C data which happens to be the maximum material temperature of the heater head during operation. For this temperature, the slope is more shallow than the temperature and will provide a more conservative creep rate (i.e., quicker rate) for a given applied stress. A possible explanation for this phenomena could be that at 820 °C the Udimet 720 LI experiences a ductility through which is typically associated with metallurgical changes. These changes will influence the mechanical properties of a material such as its strength, hardening/softening characteristics, and creep behavior (see fig. 10).

Deformation tests.—Results from a series of cyclic deformation tests are presented in figure 11. These tests were conducted at a constant strain rate of 10^{-3}/sec and a constant strain range of 1.4 percent. The strain range was chosen from the heater head structural analysis. This analysis predicted that, for a start-stop-start sequence of the power converter, the heater head would experience, as a worst case, a maximum strain range of 1.4 percent.

The hardening and softening characteristics of Udimet 720 LI are well observed in figure 10. For temperatures 725 °C and below, the material exhibits hardening behavior. At temperatures between 750 and 775 °C, Udimet 720 LI is cyclicly neutral (i.e., the material neither hardens nor softens). And for 820 °C , Udimet 720 LI appears to exhibit softening characteristics. Since Udimet 720 LI is cyclicly neutral, at temperatures close to 775 °C, all subsequent material modeling and structural analysis did not incorporate hardening/softening effects. This made the analysis less difficult and the computations less time intensive.

Fatigue tests.—Fatigue data are presented in table IV for three different welded specimens, denoted by (WU), at three different temperatures, the fatigue life had a minimum of 1000 cycles and a maximum of 206 052 cycles. This showed that, at a combination of high temperature and at low strain, the fatigue life tends to be higher. All these specimens failed at the center of the test section as expected and only three were available to test.

The life data accumulated through these tests are also represented by figure 11. It is noted that, as the temperature increased the life and the corresponding stress became lower, the life never exceeded 1000 cycles for these particular conditions.

Finite Element Results

Figures 12 to 18 are contours plots of the results of the viscoplastic and elastoplastic analyses conducted on this material at three different times during the loading cycle. For example, for the viscoplastic calculations, figures 12(a) and (b) represent the total mechanical stress and strain (Von Mises) distributions after 1 hr at the heater head as a result of the viscoplastic analysis. Figures 13(a) and (b), 14(a) and (b) show these results for the same analysis at two different time intervals, after 11 000 hr and at 12 000 hr. Similarly, Figures 15(a) and (b), 16(a) and (b) represent the stress and strain distributions for the heater head, at similar time intervals as those of the viscoplastic analysis, for the elastoplastic calculations.

The temperature profile over the heater head structure is illustrated in figure 5, which clearly shows the distribution of the temperature as a result of a steady-state heat transfer analysis. It is obvious that the heater section of the heater head maintained a uniform temperature of about 777 °C while the temperature decreased as the helium fluid temperature changed from hot to cold as it moved from top to bottom. The lowest temperature experienced by the structure was 252 °C located at the bottom portion of the heater head which is continuously cooled by the heat rejection system. A temperature gradient of about 500 °C is apparent over the length of the outer wall of the regenerator.

Thus, with the existence of the temperature gradient and with the addition of the mechanical loading, the outer wall of the regenerator exhibited the highest stresses and strains. Figures 17(a) and (b), 18(a) and (b) represent the contours of the stresses and strains obtained as a result of the viscoplastic analysis where the loading cycle covered 1000 and 10 000 hr, respectively. These cases were conducted in order to confirm experimental findings with respect to the operating life of the structure. In addition it is demonstrated from these plots that the stresses tend to relax and show very minor change as time goes from 1000 to 10 000 hr.

Life Assessment

A preliminary life assessment analysis was conducted on the heater head. The assessment was based on lifing methodology from ASME code case N-47, the subject structural analysis, and the generated creep data from this study. Due to the limited resources and test data, the life assessment does not account for stress corrosion of the Udimet 720 LI caused by the liquid sodium. It is believed that many assumptions made during this assessment will provide a conservative life approximation and therefore, any degradation of life from the sodium will not drastically change the outcome of the approximation.

Results from the finite element analysis identified several critical locations in the heater head. These locations along with their associated stress-temperature conditions concurred with the designer's approximations. The two most critical locations in the heater head are located in the starfish's finned section; namely, (1) the leading tip of the fins and (2) the bottom of the fins in the gas passage area. At these locations, the temperature of the Udimet 720 LI is at a maximum of 775 °C and the calculated stresses are at a maximum of 235 and 140 MPa. The predominant failure mode for these areas will be creep. In addition to the relatively high temperature-stress condition in these areas, the Udimet 720 LI will be subjected to corrosive liquid sodium. Liquid sodium has a tendency to attack grain boundaries of alloys and has a high affinity toward nickel. Also, the gas passage wall thickness contributes to the criticality of this area. The combination of the starfish's thin wall thickness and the requirement for a creep resistant (large grain) Udimet 720 LI makes it extremely vulnerable for failure. In the present design the grain size and gas passage wall thickness have been optimized to have an average of 3 to 5 grains spanning its thickness. Even though more grains going across that thickness is more desirable from a structural integrity viewpoint, it will be shown that there are enough factors of safety in the design to allow for the heater head to meet its design life goals.

The design life of the starfish heater head is 60 000 hr of continuous operation at 775 °C. Ideally, to conduct a life approximation analysis for this type of application, 30 000- to 60 000-hr creep data for Udimet 720 LI would be required. This type of data does not exist for Udimet 720 LI. In fact, there are very few materials that have creep data lasting that long. A good life approximation can be made based on the data that has been generated from this study. By making the assumption that the calculated steady-state creep rates remain constant over the period of interest and the heater head operation is constant (i.e., does not experience any on-off cycles), a preliminary life approximation can be made from figure 9. At approximately 235 MPa the calculated maximum heater head stress loacted at the fin tip, the steady-state creep rate is 4.5×10^{-6} percent/hr. By using a maximum creep strain limit (ASME code case N-47) of 1 percent as a failure criterion, it would take approximately 222 000 hr to reach that creep strain level. This time to 1 percent creep strain far exceeds the required design life of 60 000 hr. Conversely, by using the same creep rate for 60 000 hr, the Udimet 720 LI would have accumulated only 0.27 percent creep strain which is below the failure criterion of 1percent .

In the location of the gas passages, the maximum heater head stresses are approximately 140 MPa. By using a stress value of 280 MPa or a stress value two times larger than the calculated stress from figure 9, a steady-state creep rate of 2×10^{-5} percent/hr is obtained. This creep rate would provide a heater head life of 50 000 hr. Note that this life level is still within the acceptable design limits even though it is less than the 60 000-hr design goal, because the stress level that was used is double the actual calculated stress for this location.

Therefore, with such large margins of safety (or conservativeness) it appears that the heater head will meet the design life goals of 60 000 hr even with a decrease in life caused by a sodium interaction with the Udimet 720 LI.

CONCLUSIONS

Low-cycle fatigue and creep experiments on a cast-wrought nickel-base superalloy, Udimet 720 LI (Low Inclusion), and a combined finite element viscoplastic, elastoplastic analyses for the Stirling starfish heater head were conducted. All testing was performed at temperatures of 625 to 820 °C in air. This work was initiated to generate a unique consistent data base in support of a life prediction modeling effort aimed at characterizing Freed's viscoplastic model and verifying the key damage mechanisms. The following conclusions can be drawn:

1. The test program was successfully completed and a fatigue data base was generated for this material for a range of temperature variations.
2. Temperature effects were shown to have a strong influence on the fatigue life of this material. It was noted that the life decreased as the temperature increased. The maximum strain range was about 5 percent. Although not having enough specimens to run more fatigue tests may have limited the findings to some extent, additional confirmation with regard to the strength and the life limitations of this alloy can be estimated through applicable life prediction methodologies available in the literature to support the experimental findings.
3. The characterization of Freed's viscoplastic model was successfully implemented and applied to a Stirling engine heater head. The data obtained through the viscoplastic analysis coincided well with the experimental results and also with the elastoplastic calculations. Running the analysis to cover a 10 000-hr period showed that the heater head can last the design lifetime of 60 000 hr since the stresses relaxed as expected toward the end of the loading cycle.
4. The location of extensive deformation in the component depended on the duration of the loading cycle, thereby implying that the failure of the component may also depend on the duration of the loading cycle. Furthermore, the results showed that structural analysis by a viscoplastic model that incorporates two internal state variables was capable of qualitatively predicting the experimentally observed behavior of the material.
5. Based on the preliminary life assessment, it appears that the heater head will need its 60 000-hr design goals. Factors of safety in the thin-walled gas passages appear to be within acceptable limits (a factor of 2 in stress), and therfore liquid soduim attack in this location should not be a concern.

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TABLE I.—CHEMICAL COMPOSITION OF UDIMET 720 (Internal report from Sczerzenie, et al.: Udimet 720 Alloy. Special Metal Corp. Report TR–8–002, May 1978)

Element	Weight percent
Carbon	0.01
Manganese	0.01
Silicon	0.01
Chromium	15.90
Nickel	Bal.
Cobalt	14.66
Iron	0.07
Monel	3.03
Tungsten	1.24
Titanium	5.08
Aluminum	2.70
Boron	0.0154
Zirconium	0.029
Sulfur	0.0011
Phosphorus	0.001
Copper	0.03

TABLE II.—TENSILE DATA FOR UDIMET 720

Specimen	Temperature, °C	Strain rate, 1/sec	Modulus, GPa	Stress, σ, at 0.1 percent, MPa	Stress, σ, at 0.2 percent, MPa
UD9	775	0.0001	172	744	771
UD8	775	0.0001	169	763	758
UD2	775	0.0003	171	775	802
UD5	775	0.0010	183	758	787
UD10	675	0.0010	189	822	853
UD11	820	0.0010	171	701	698
UD12	675	0.0010	184	785	816
UD13	625	0.0010	188	790	819
UD21	700	0.0010	186	821	853

TABLE III.—STEADY-STATE CREEP DATA FOR UDIMET 720 LI

Specimen	Temperature, °C (K)	Stress, σ, MPa	Creep rate, 1/hr
CR1	820 (1095)	331	4.22×10^{-3}
CR2	820 (1095)	165	51.9×10^{-4}
CR3	775 (1050)	662[a]	1.15×10
CR4	775 (1050)	414	9.30×10^{-4}
CR5	775 (1050)	331	7.19×10^{-4}
CR6	675 (950)	827	7.86×10^{-2}
CR7	675 (950)	745	1.17×10^{-3}
CR8	675 (950)	662	5.19×10^{-5}
CR9	675 (950)	331	3.50×10^{-4}
CR10	675 (950)	331	1.94×10^{-5}
CR11	625 (900)	827	1.15×10^{-3}
CR12	625 (900)	745	7.35×10^{-4}
CR13	625 (900)	662	1.38×10^{-3}
CR14	625 (900)	414	6.69×10^{-5}

[a]Specimen ruptured after 4 hr.

TABLE IV.—LOW CYCLE FATIGUE DATA FOR UDIMET 720 LI ON WELDED SPECIMENS (FREQUENCY, 0.2 Hz)

Specimen	Temperature, °C	Strain, mm/mm	Life cycles
WU720–1	690	0.33	19 000
WU720–2	620	0.58	1 000
WU720–3	775	0.313	206 052

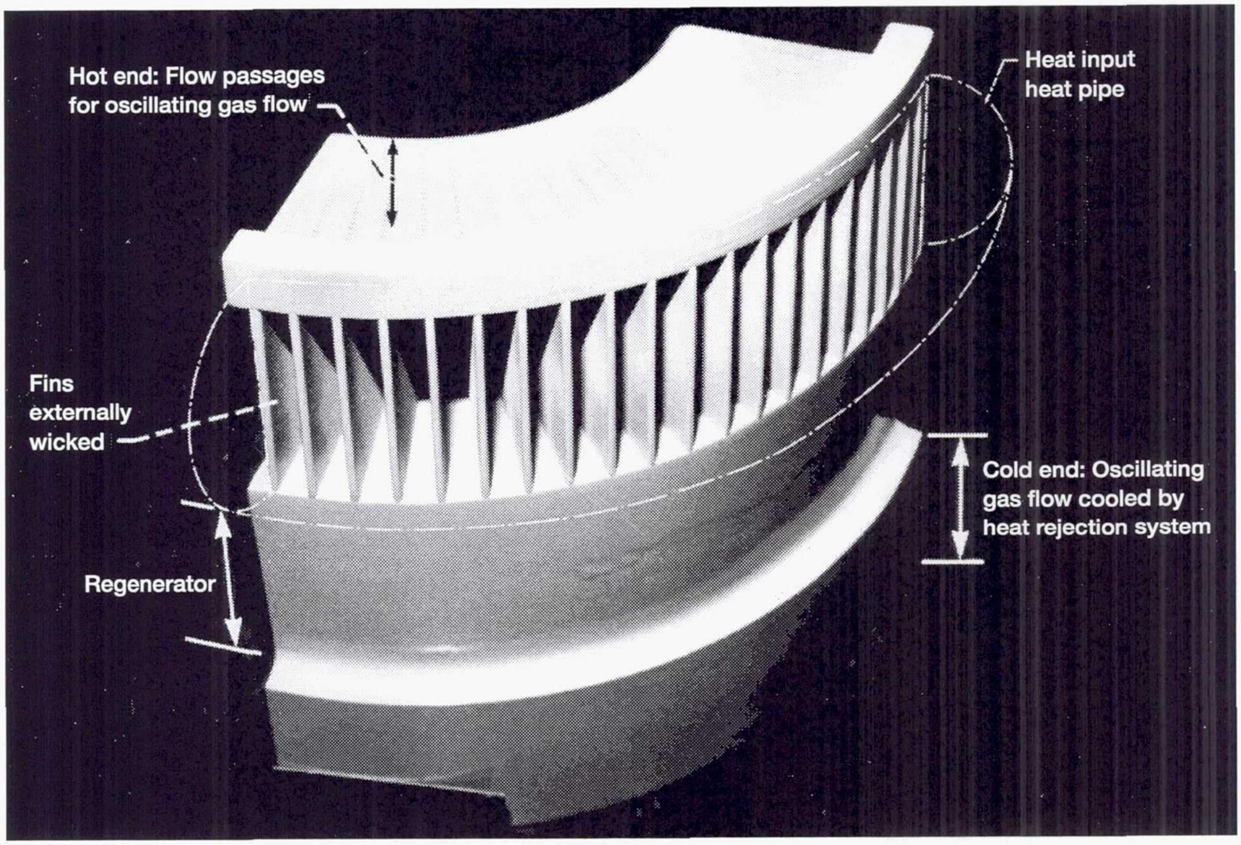

Figure 1.—Section of "starfish" Stirling engine heater head showing thin-walled fins.

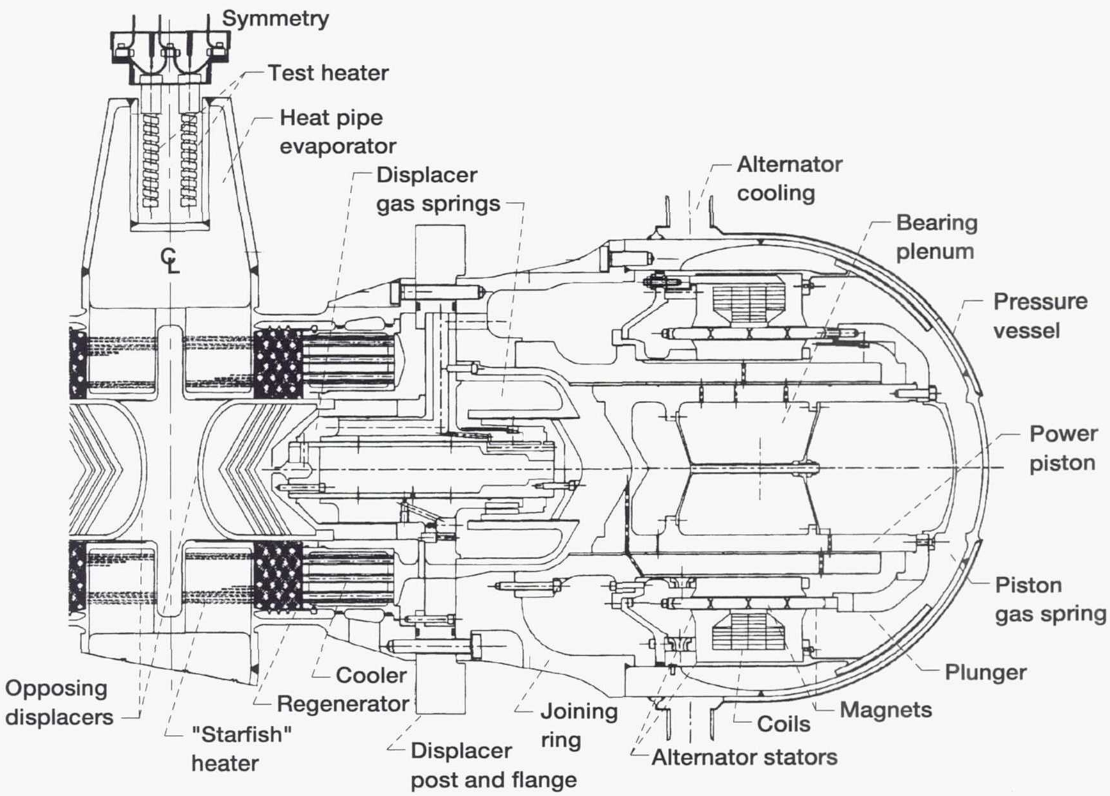

Figure 2.—Cross section of Stirling Power Converter.

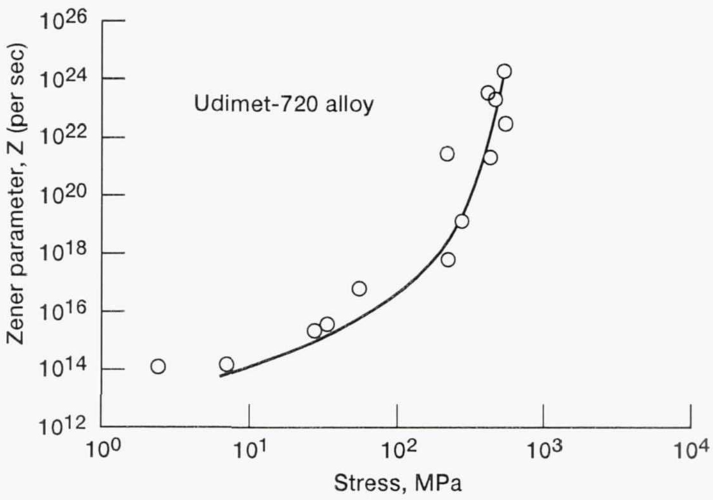

Figure 3.—Zener parameter as function of stress.

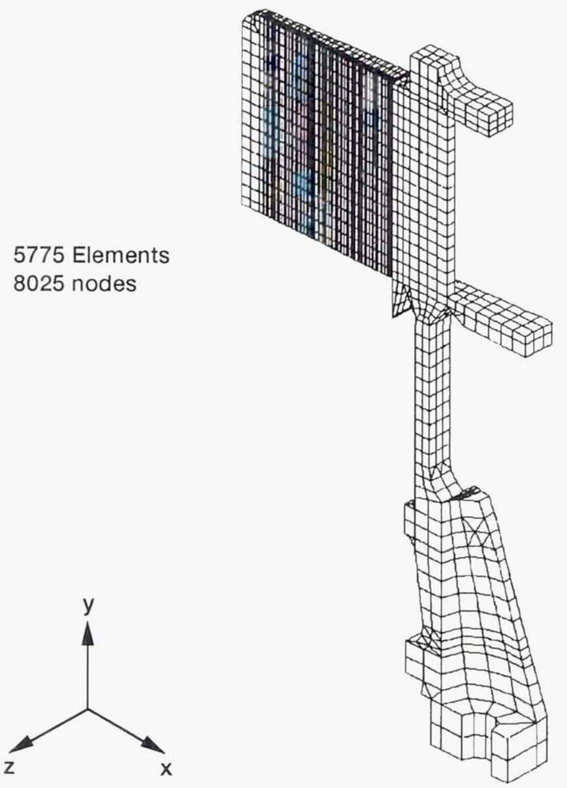

Figure 4.—Stirling heater head finite element model.

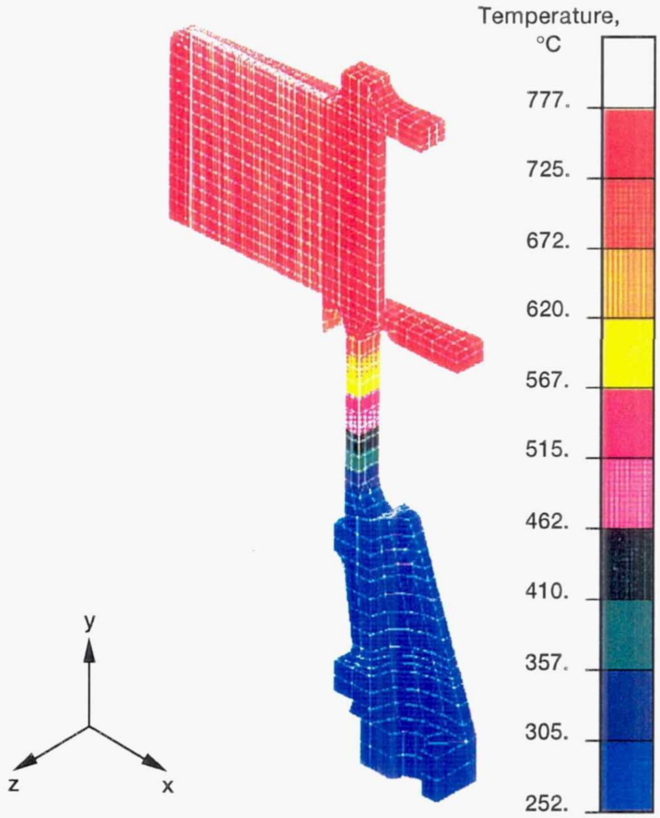

Figure 5.—Steady-state temperature distribution of heater head.

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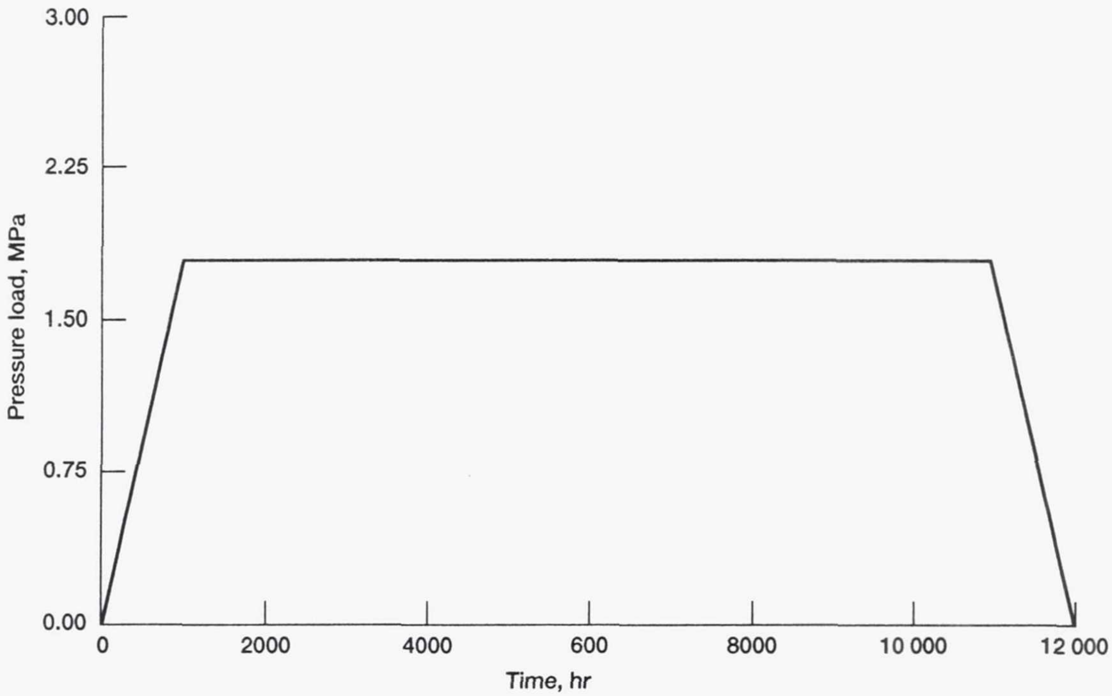

Figure 6.—Loading cycle used for analyses.

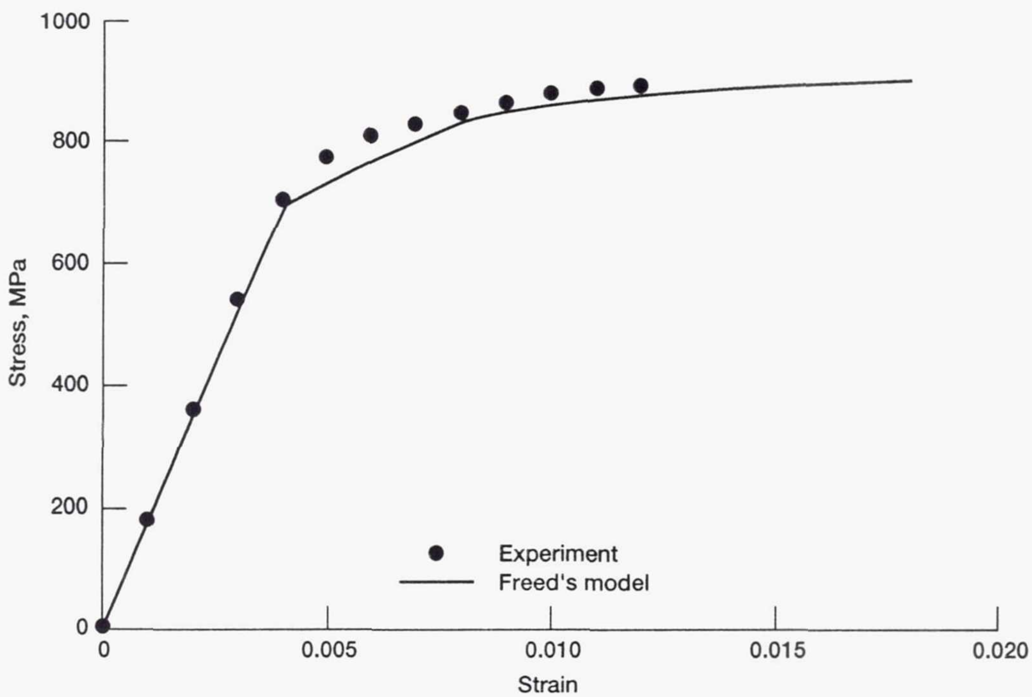

Figure 7.—Stress-strain output for uniaxial test sample comparing experiment and prediction for Udimet 720 LI at 675 °C.

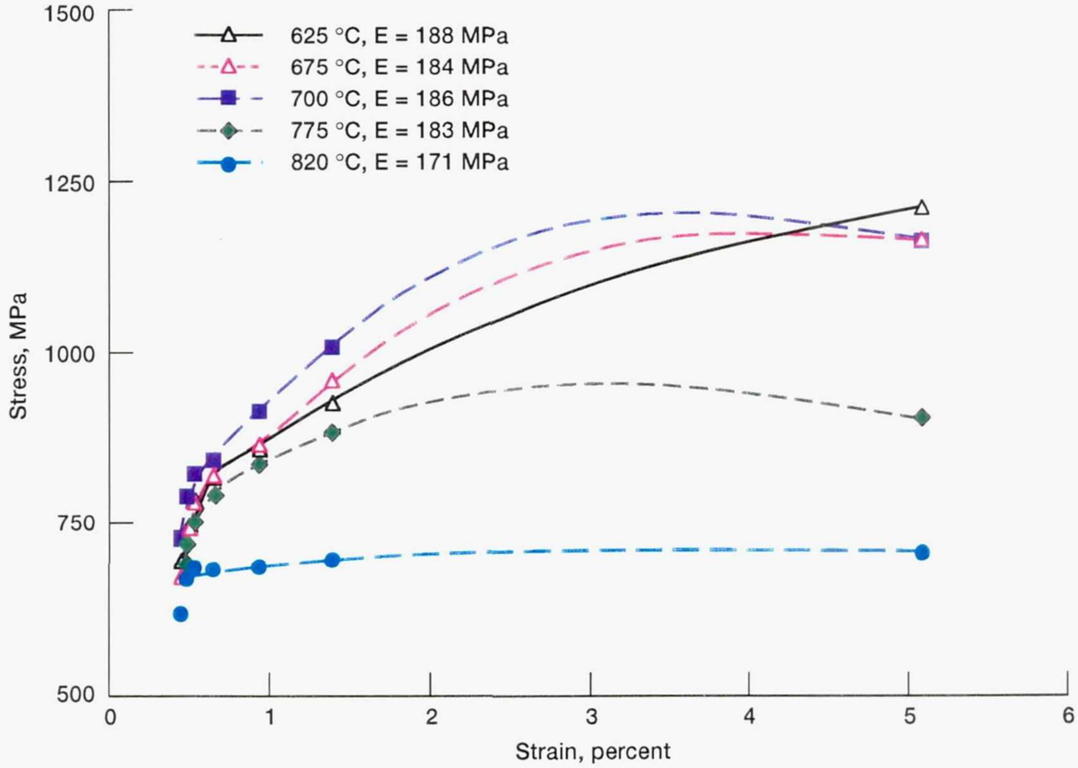

Figure 8.—Deformation response (stress-strain relation) for Udimet 720 LI.

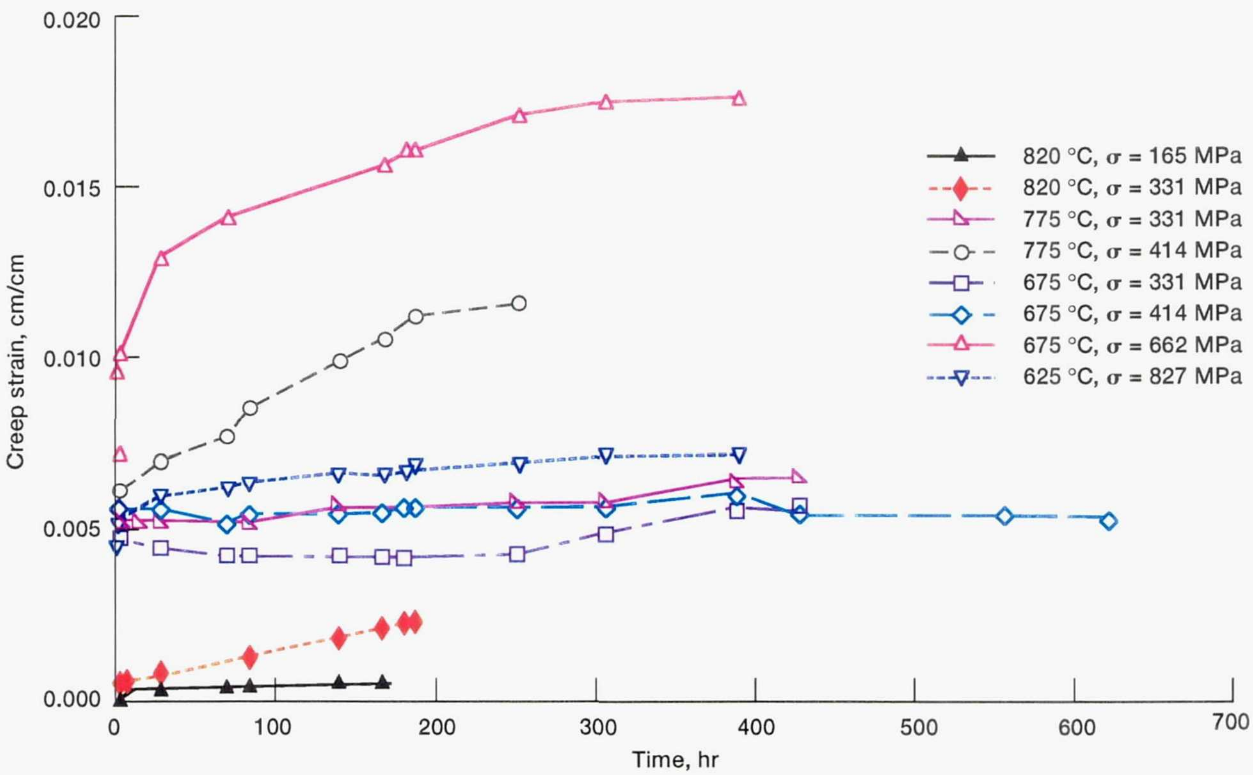

Figure 9.—Creep strain as function of time for Udimet 720 LI.

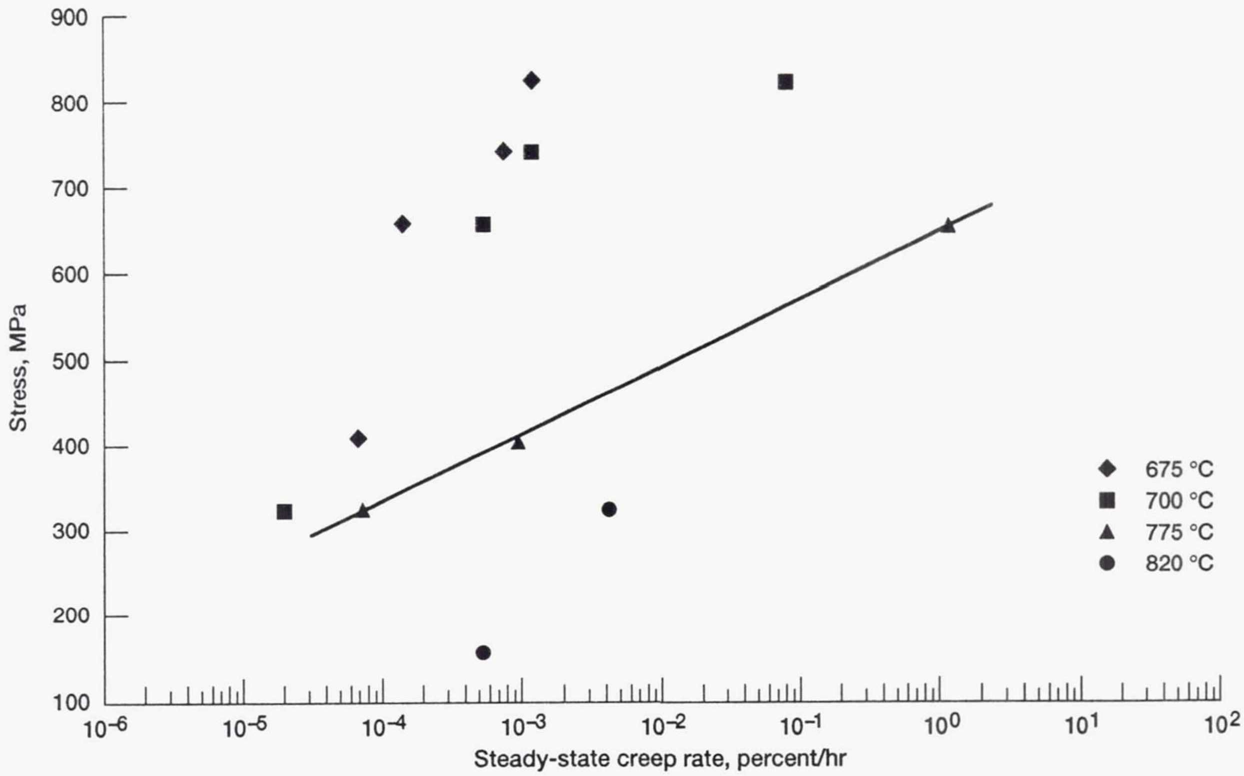

Figure 10.—Cyclic deformation for Udimet 720 LI.

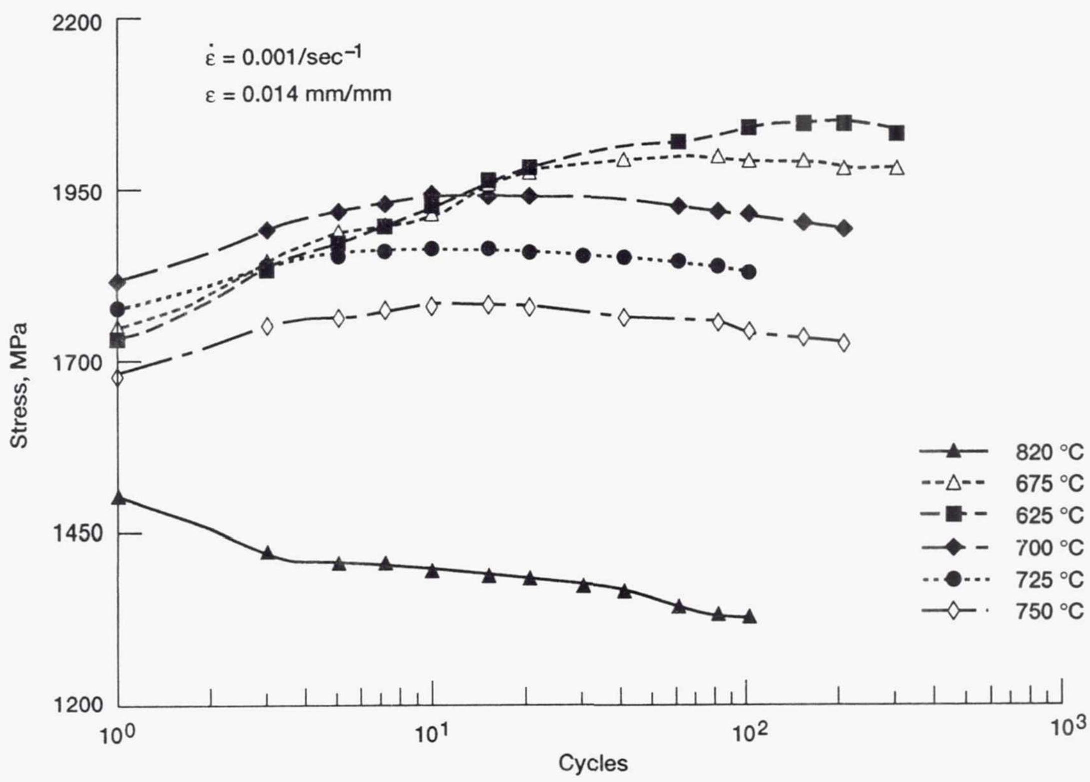

Figure 11.—Steady-state creep rate as function of temperature for Udimet 720 LI.

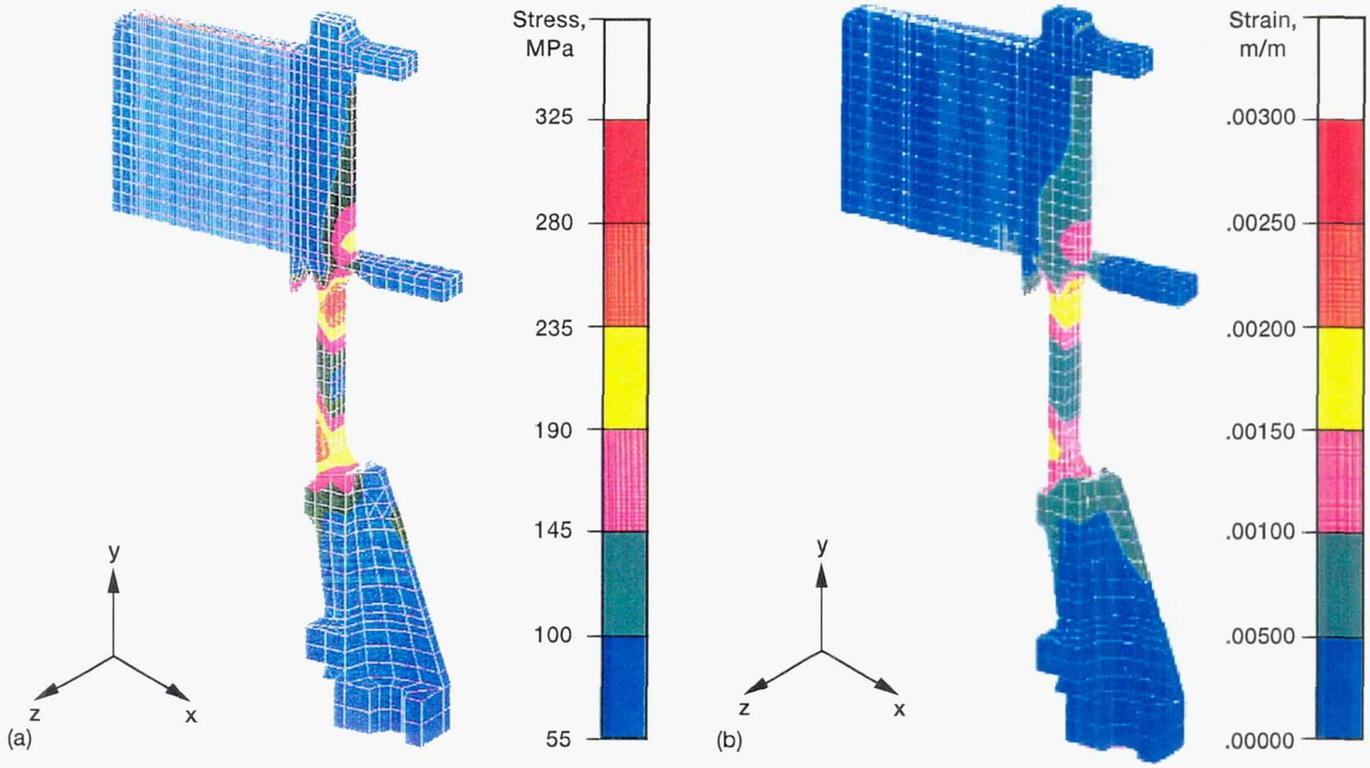

Figure 12.—Von Mises stress and equivalent mechanical strain predicted by Freed's viscoplastic model after 1 hr. (a) Von Mises stress. (b) Equivalent mechanical strain.

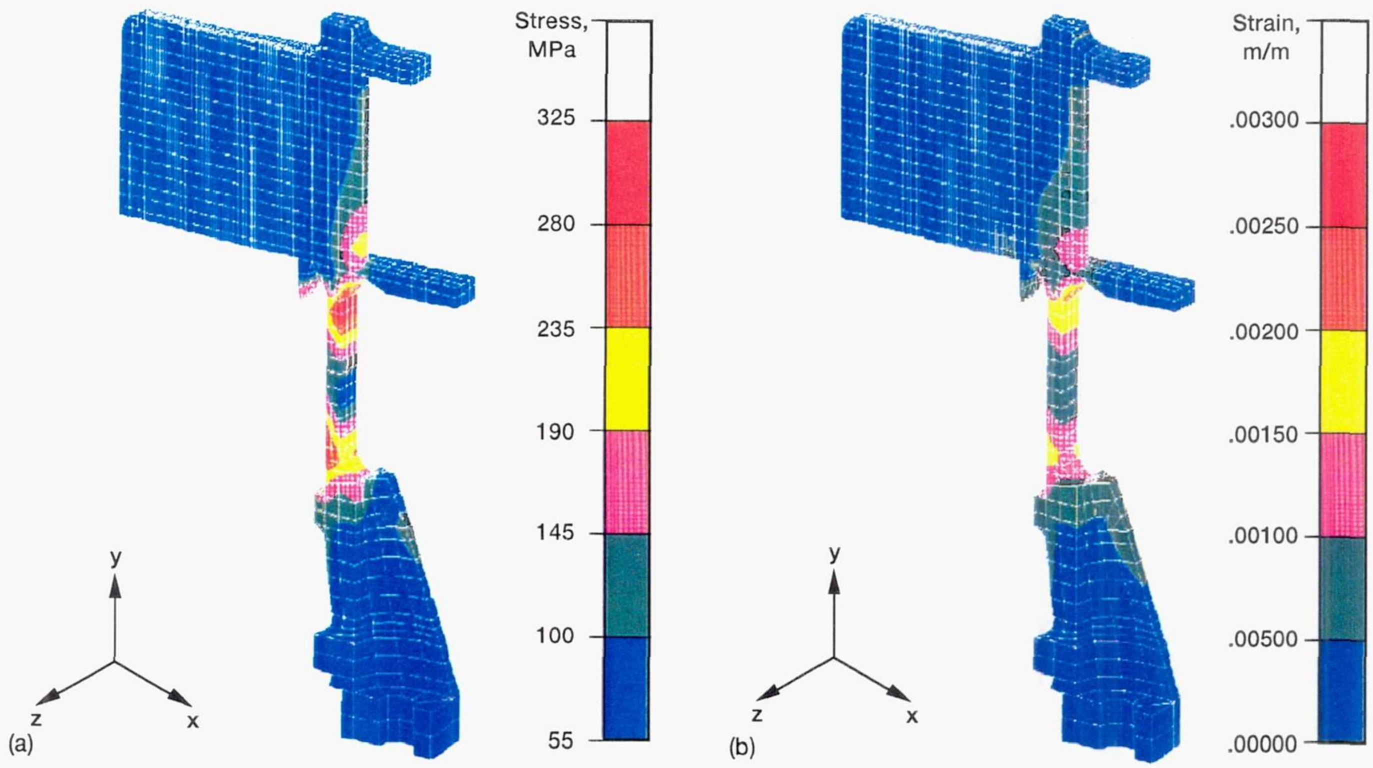

Figure 13.—Von Mises stress and equivalent mechanical strain predicted by Freed's viscoplastic model after 11 000 hr. (a) Von Mises stress. (b) Equivalent mechanical strain.

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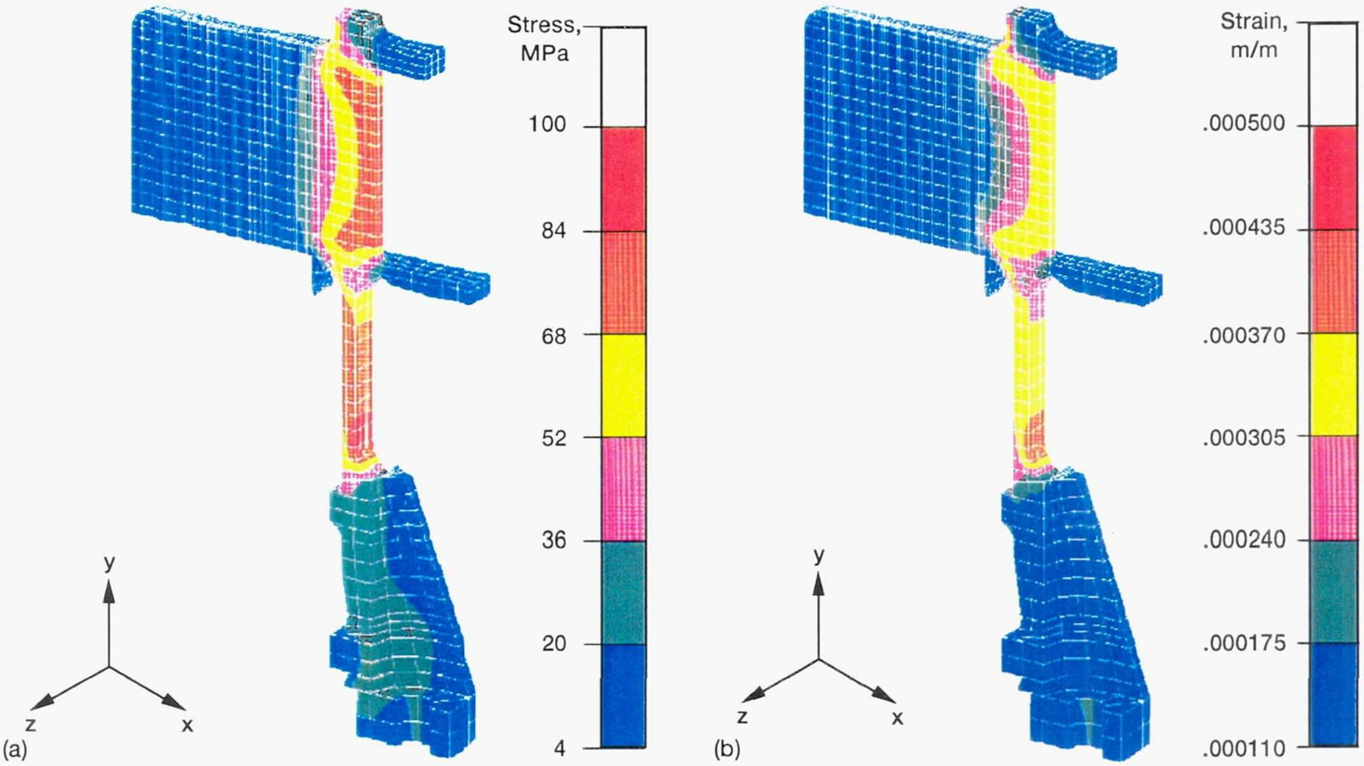

Figure 14.—Von Mises stress and equivalent strain predicted by Freed's viscoplastic model after 12 000 hr. (a) Von Mises stress. (b) Equivalent mechanical strain.

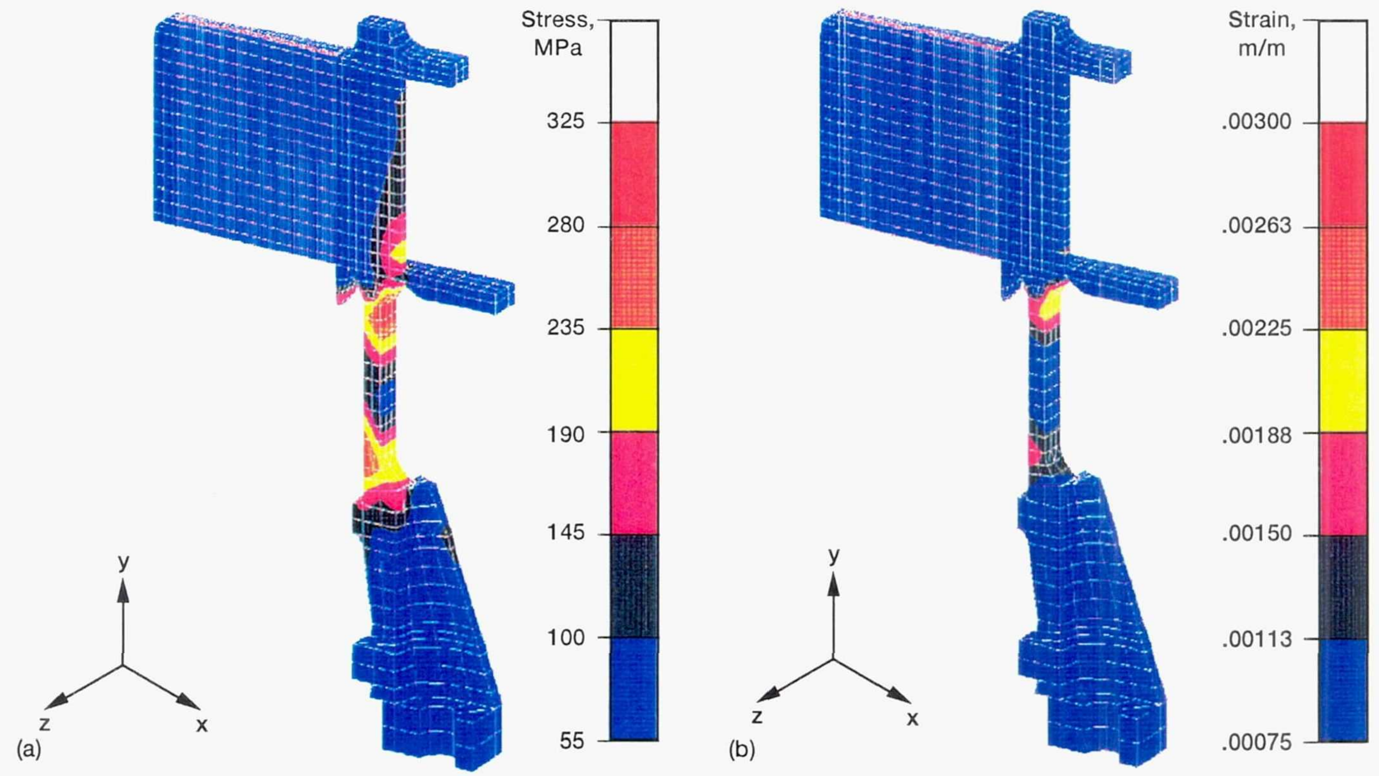

Figure 15.—Von Mises stress and equivalent mechanical strain predicted by elastoplastic analysis after 1 hr. (a) Von Mises stress. (b) Equivalent mechanical strain.

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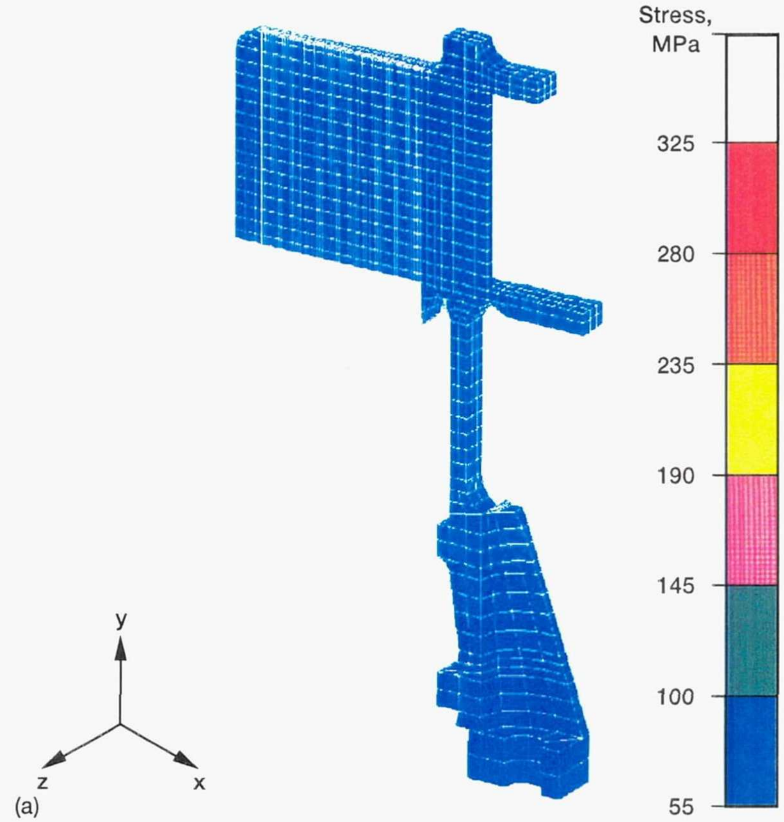

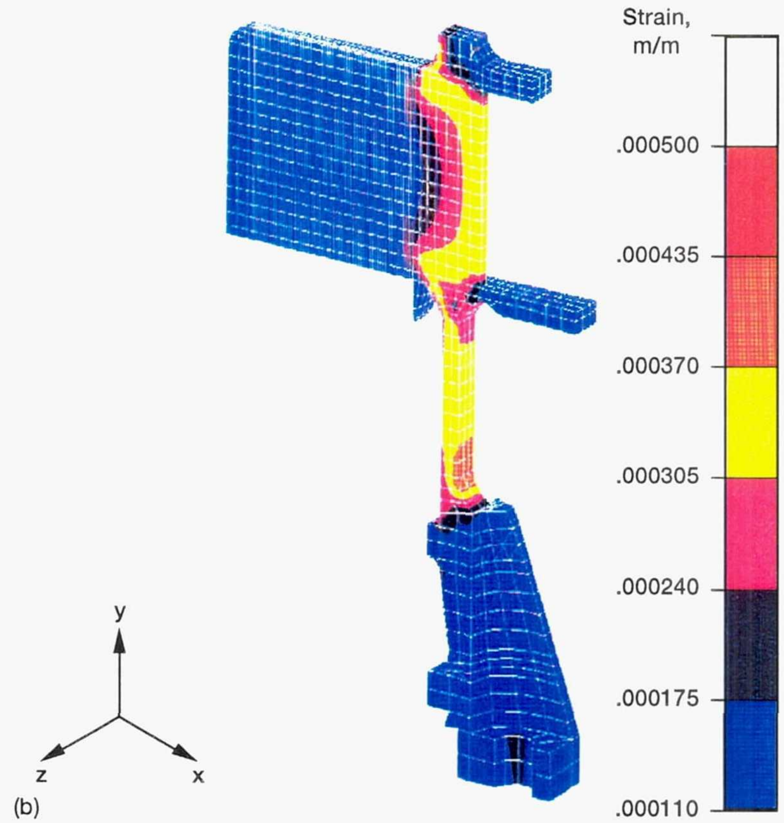

Figure 16.—Von Mises stress and equivalent mechanical strain predicted by elasto-plastic analysis after 12 000 hr. (a) Von Mises stress. (b) Equivalent mechanical strain.

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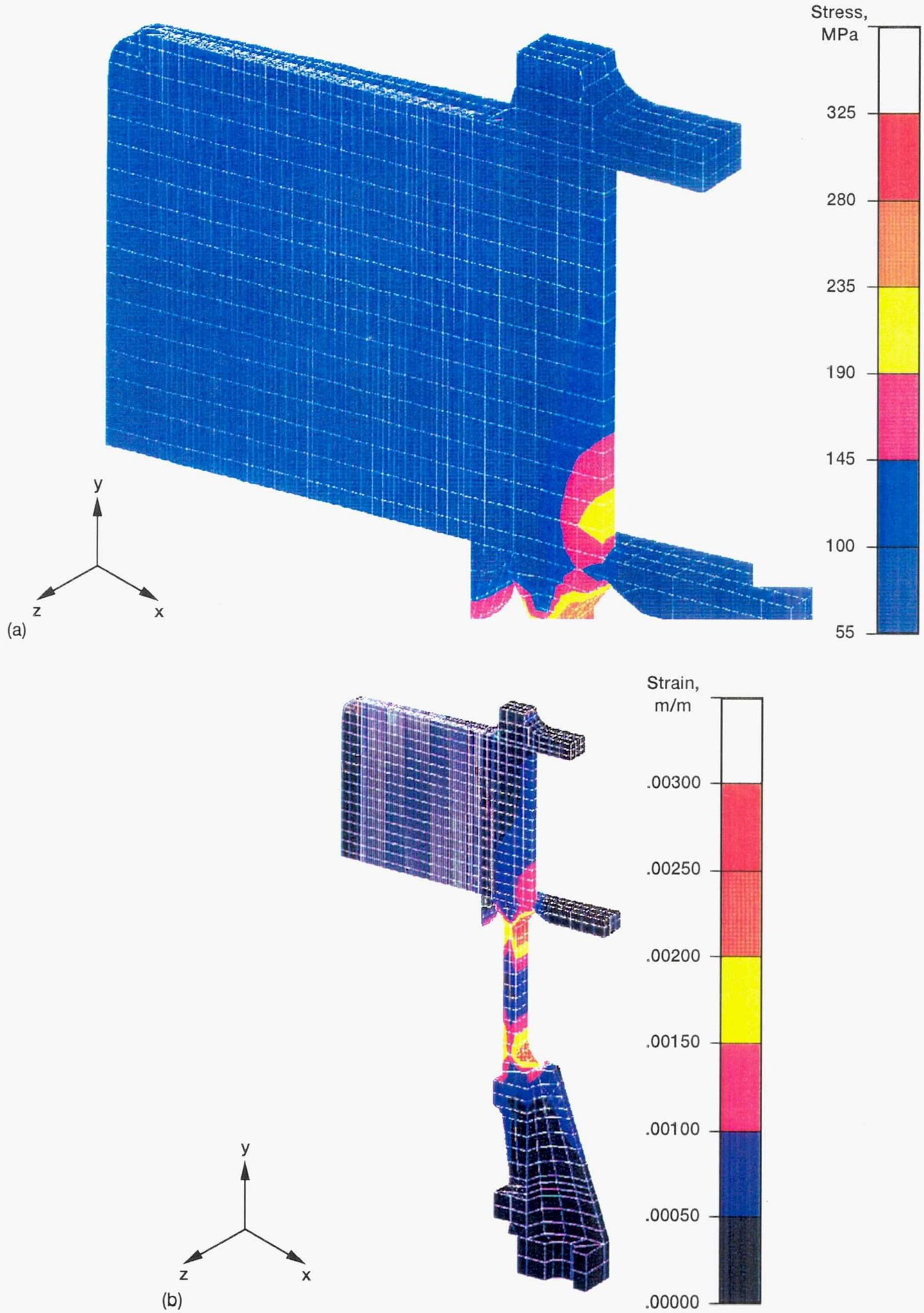

Figure 17.—Von Mises stress and equivalent mechanical strain predicted by Freed's viscoplastic model after 1001 hr. (a) Von Mises stress. (b) Equivalent mechanical strain.

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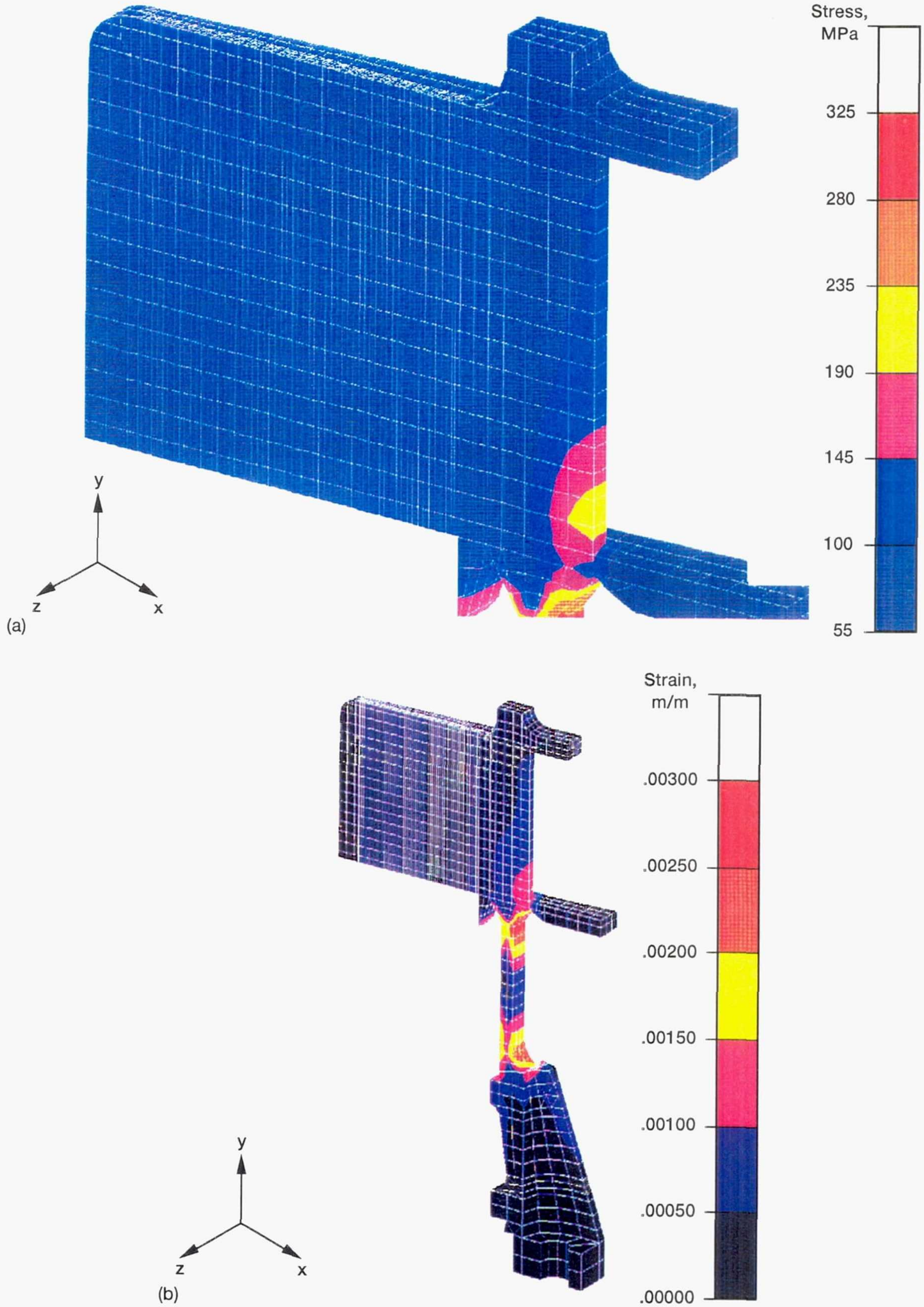

Figure 18.—Von Mises stress and equivalent mechanical strain predicted by Freed's viscoplastic model after 10 001 hr. (a) Von Mises stress. (b) Equivalent mechanical strain.

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13. ABSTRACT *(Maximum 200 words)*

NASA has identified the Stirling power converter as a prime candidate for the next generation power system for space applications requiring 60 000 hr of operation. To meet this long-term goal, several critical components of the power converter have been analyzed using advanced structural assessment methods. Perhaps the most critical component, because of its geometric complexity and operating environment, is the power converter's heater head. This report describes the life assessment of the heater head which includes the characterization of a viscoplastic material model, the thermal and structural analyses of the heater head, and the interpolation of fatigue and creep test results of a nickel-base superalloy, Udimet 720 LI (Low Inclusions), at several elevated temperatures for life prediction purposes.

14. SUBJECT TERMS
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